# CARLSBERG POSITIONS OF PLANETS COMPARED WITH JPL DE403

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**Abstract.** The Carlsberg meridian telescope has made nearly 20 000 observations of outer Solar System objects since it began operation in 1984. A preliminary version of the Hipparcos catalogue has been used to refer the positions to the International Celestial Reference Frame (ICRF). The observed positions of the major planets are compared with JPL DE403 which is also referred to the ICRF. The agreement with DE403 is good, except for the declination of Jupiter where there is a systematic difference reaching 0.″15 in 1995. The cause of this discrepancy is being investigated at JPL with recent VLBI observations of *Galileo*.

## 1. Carlsberg meridian telescope

The Carlsberg meridian telescope has been operating almost continuously since 1984 on the island of La Palma at the international observatory *Roque de los Muchachos* of the Instituto Astrofisica de Canarias. It is situated at a latitude of 28.°7 north and an altitude of 2400 m and is operated jointly by Copenhagen University Observatory, the Royal Greenwich Observatory and the Real Instituto y Observatorio de la Armada, San Fernando. The operating procedure is described in Helmer and Morrison (1985) and a description of the scanning-slit micrometer and photoelectric detector system can be found in Helmer *et al.* (1991). The positions of the Solar System objects are measured once nightly as they cross the prime meridian. Only one satellite in each planetary system is observed each night. About 2% of the observing time is spent on Solar System objects.

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## 2. Observations

The observations discussed in this paper are published in an annual series of catalogues, Carlsberg Meridian Catalogues Numbers 1–9 (1985–1996). The number of observations of Solar System objects in each catalogue is listed in Table 1. The accuracy of the positions is a function of zenith distance

TABLE 1. Carlsberg observations of outer Solar System objects.

| Year | Ganymede | Callisto | Rhea | Titan | Hyperion | Iapetus |
|---|---|---|---|---|---|---|
| 1984 | – | – | – | – | – | – |
| 1985 | – | – | – | – | – | – |
| 1986 | – | 67 | – | – | – | – |
| 1987 | – | 26 | – | 70 | – | – |
| 1988-89 | – | 44 | – | 89 | – | – |
| 1990 | – | 24 | – | 40 | – | 30 |
| 1991–92 | 24 | 76 | 7 | 63 | 4 | 59 |
| 1992–93 | 35 | 28 | 5 | 39 | 17 | 36 |
| 1994–95 | 46 | 55 | – | 26 | 21 | 28 |

| Year | Uranus | Oberon | Neptune | Pluto | Minor planets(~60) |
|---|---|---|---|---|---|
| 1984 | 54 | – | 78 | – | 667 |
| 1985 | 64 | – | 47 | – | 1632 |
| 1986 | 101 | – | 103 | – | 2501 |
| 1987 | 65 | – | 64 | – | 2030 |
| 1988–89 | 105 | – | 110 | 32 | 2467 |
| 1990 | 76 | – | 105 | 11 | 1106 |
| 1991–92 | 148 | 8 | 184 | 107 | 2108 |
| 1992–93 | 57 | 21 | 72 | 26 | 1793 |
| 1994–95 | 55 | 25 | 66 | 46 | 2495 |

and magnitude (see Table 2, Morrison and Buontempo, 1996). The best accuracy of $\pm 0''.12$ is obtained in the zenith (Dec $\sim +30°$ ). The accuracy has improved with time as a consequence of improvements in instrumentation and processing of the raw data. The positions are referred to the Carlsberg reference frame which is a smoothed FK5 system, as described by Morrison *et al.* (1990).

The Carlsberg reference frame is generally within $0''.05$ of the ICRF, but there are distortions in the frame reaching $0''.07$ in right ascension and $0''.10$ in declination in the region of the ecliptic (Argyle *et al.*, 1996). These distortions carry through to the planetary observations, and it is desirable that they should be removed. A preliminary version of the Hipparcos cata-

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logue (H37), rotated to the ICRF, has been used to measure the systematic errors of the Carlsberg frame with respect to the ICRF. These errors have been subtracted from the observed positions, and mean values and their standard errors have been computed for each opposition.

## 3. Comparison with JPL DE200 and DE403

The standard ephemeris, JPL DE200, was used as the basis for the comparison with the observed opposition means. The differences, Carlsberg minus DE200, for the outer planets, except Mars, are shown in Figure 1 and Figure 2.

Where observations of satellites were made, an ephemeris based on the theory of their orbital motion was used to reduce the observed positions to the barycentre of the system. So the plots of the residuals for Ganymede and Callisto, for example, effectively show the comparison of Jupiter with DE200, the errors in the theory being negligible in the present context.

The DE200 ephemeris is now out-of-date and it is more meaningful to compare the opposition means with DE403 which has been fitted to more recent data and is also referred to the ICRF through the use of radio observations (see Standish 1996). The differences, DE403–DE200, are also shown on the plots as a continuous wavy line.

So, both the observations and DE403 are plotted with respect to DE200, and they are referred to the same frame — the ICRF. The agreement between the Carlsberg observations and DE403 is generally good, except for the declination of Jupiter, and this requires some comment.

The ephemeris in the *Connaissance des Temps* (CdT), which is based on the G–5 theory (Arlot, 1982), was used to reduce the satellite positions to the barycentre of the Jovian system. This ephemeris cannot introduce errors in the comparison between observation and theory as large as those depicted in the plot.

The explanation of these offsets in declination lies in the construction of DE403 which attempts to reconcile the inconsistencies between the long series of optical data, which are referred to the FK5 frame, and the high-precision radio data which are basically referred to the ICRF. However, the Carlsberg points plotted in Figure 1 are also referred to the ICRF, and yet they are inconsistent with DE403. Optical observations from the US Naval Observatory and Hipparcos support the Carlsberg results. So, there appears to be a fundamental inconsistency between the optical and radio data. The radio data comprise observations of the Pioneers, Voyagers, Ulysses and Galileo missions, as well as VLA measurements. The declination derived from the Voyagers is particularly inconsistent with the optical observations and the relatively high weight given to the Voyagers is forcing the DE403 ephemeris away from the optical observations. This problem may soon be

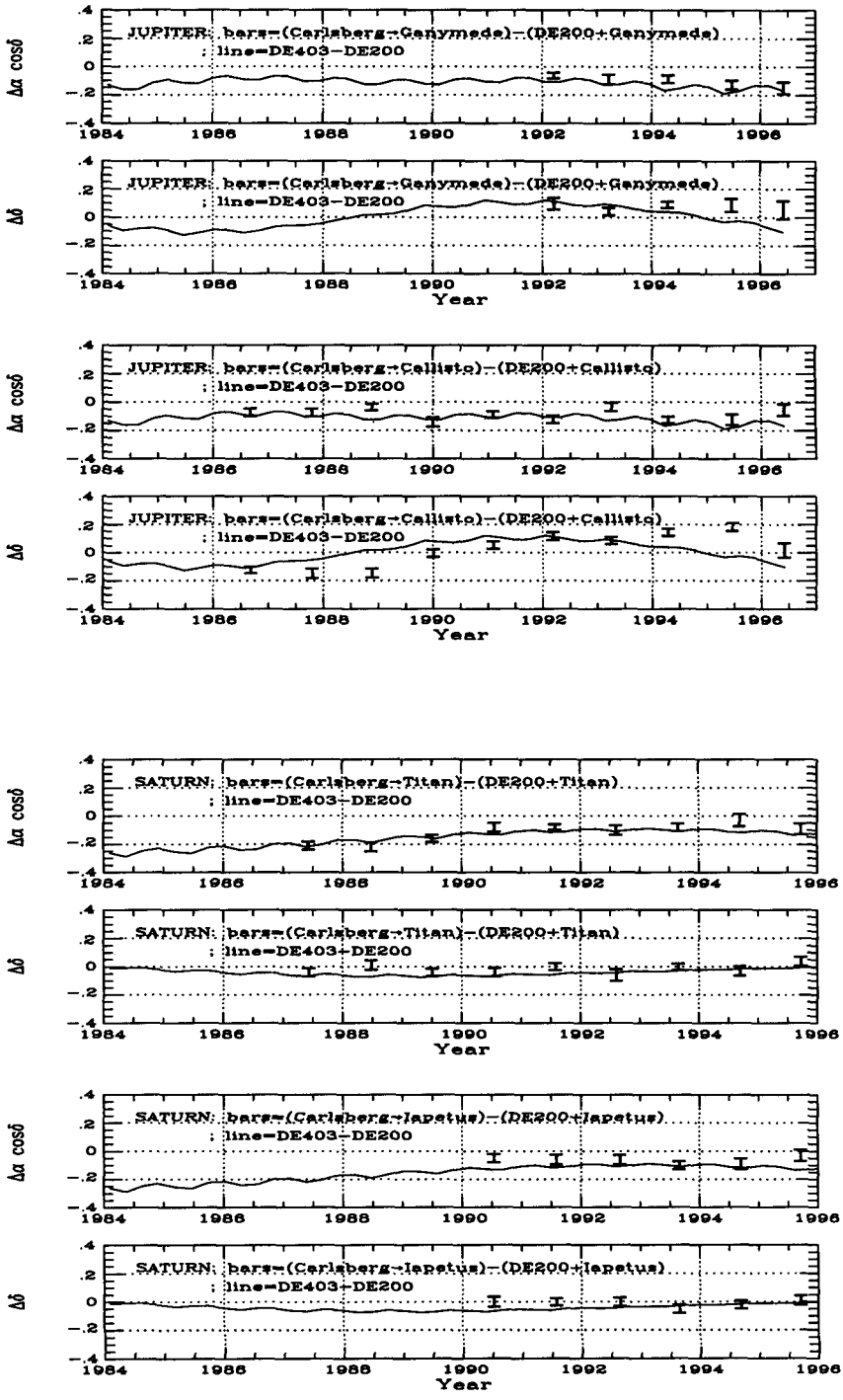


*Figure 1.* Comparison of Carlsberg opposition means for Jupiter and Saturn with DE200 and DE403 (unit=arcsec).

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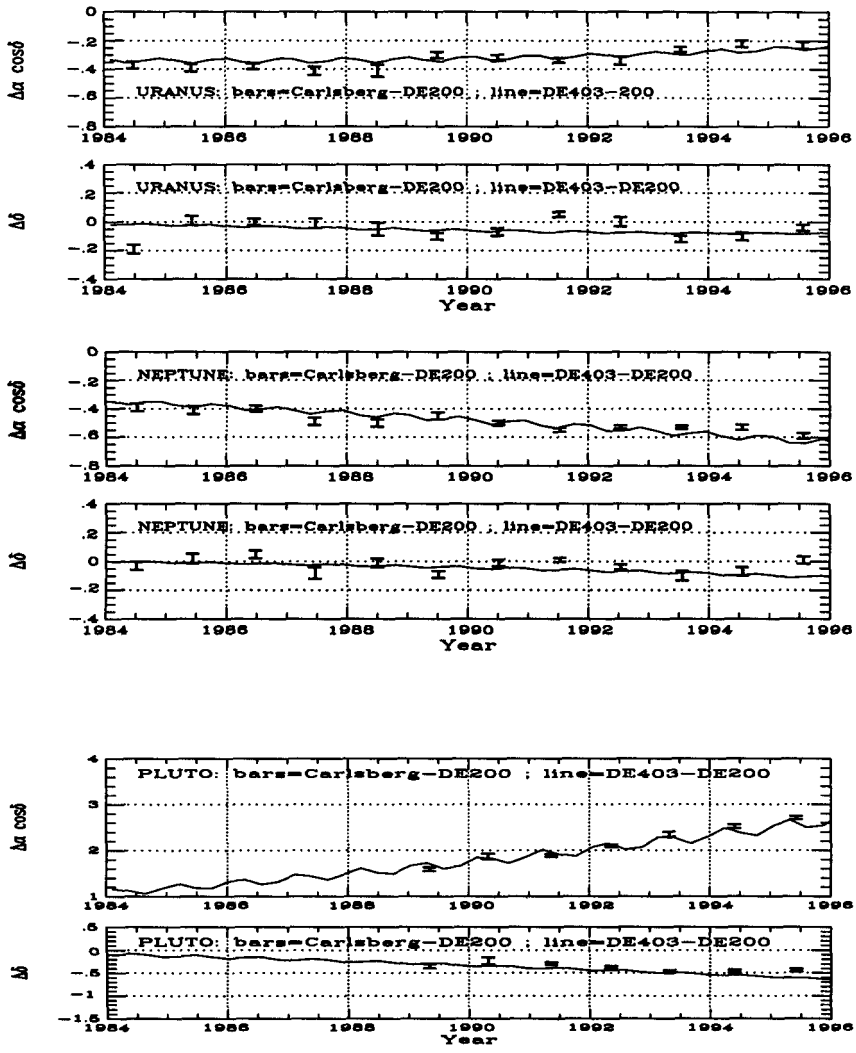


*Figure 2.* Comparison of Carlsberg opposition means for Uranus, Neptune and Pluto with DE200 and DE403 (unit=arcsec).

resolved by obtaining VLBI observations of Galileo which is in orbit round Jupiter at present.

## 4. Future developments

Improvements in the accuracy of the optical observations are now being obtained with CCD detectors on meridian telescopes. With the reference

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frame provided by Hipparcos/Tycho, this will reduce both the systematic and accidental errors of optical positions to $\sim 0''.05$ for a single observation.

## 5. Conclusions

The considerable run-offs from DE200 in the past 15 years and the absence of high-precision VLBI data beyond Jupiter, emphasize the need to continue monitoring the positions of the planets in the outer Solar System. There is an unresolved problem in declination in the latest JPL ephemerides of Jupiter.

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